Indian J. Phys. **70A** (3) 345–354 (1996)

IJP A
– an international journal

THE INCREDIBLE SUCCESS OF THE QUARK MODEL

André MARTIN
Theory Division, CERN
1211 Geneva 23, Switzerland

Abstract: We review the successes of the potential models of hadrons in terms of quarks, in particular the recent observations at LEP, CDF and the CERN hyperon beam.

Keywords: quark potential models, hadrons, hyperon beam

PACS Nos: 12.39.Pn, 14.65.-q

I would like to say that I am delighted to contribute to this Festschrift dedicated to Haridas Banerjee, a great Indian theoretician with great originality who has treated fundamental problems without letting himself be influenced by the "fashion". It is for me a pleasure and also a kind of duty to write this paper since now I belong to your community after my recent election as a fellow of the National Science Academy, India.

Today, my talk will deal with hadron spectroscopy in terms of quarks interacting by a potential.

As we know, few people considered quarks as real particles at the beginning, the most notable exceptions being Dalitz[1] and Zweig himself[2]. After the discovery of charmonium and upsilon, things changed and potential models of the $c\bar{c}$ and $b\bar{b}$ systems were proposed. After a short period of euphoria, all sorts of seemingly convincing arguments were given against potential models, in particular by the ITEP group. Yet the predictive power of these potential models is considerable and there should be no reason to speak again about it today if it were not that there are still sceptics and that some of the predicted particles have been very recently discovered or are going to be discovered by accelerators like the SPS, LEP, the TEVATRON, or the LHC.

Starting from theoretical problems concerning the Schrödinger equation I found myself led to propose a very naïve potential model for the $c\bar{c}$, $b\bar{b}$, $s\bar{s}$ and $c\bar{s}$ systems based on the observation, previously made by Quigg and Rosner that the spacings between the various $b\bar{b}$ energy levels were not very different from the spacings between the corresponding $c\bar{c}$ energy levels (Figs. 1 and 2) in spite of the fact that the b quark is about three times heavier than the c quark.

Should the spacings have been exactly the same, one would have concluded that the flavour-independent potential between a quark and an antiquark is $C \log r/r_0$.

The potential[3] $V = -8.064 + 6.87r^{0.1}$, in units of powers of GeV with masses $m_c = 1.8, m_b = 5.174$ supplemented by a point-like spin-spin interaction adjusted to the $J/\psi - \eta_c$ mass difference gives an excellent fit to the data as shown in Fig. 3. Also on Fig. 3 is the fit by a QCD-inspired potential due to Buchmüller and collaborators[4]. One can decide to include also the strange quark in the game (a suggestion of M. Gell-Mann) to see what happens.

Taking $m_s = 0.518$ GeV/c^2 to fit the ϕ mass, one gets

$m_{\phi'} = 1.634$ GeV/c^2	(exp 1.650)
$m_{D_S} = 1.99$	(exp 1.97)
$m_{D_S^*} = 2.11$	(exp 2.11)
$m_{D_S^{**}}(L=1) = 2.537$	(Argus 2.536)
$m_{B_S} = 5.354$	(Aleph gives 5.373 GeV/c^2 CDF gives 5.367) A 1989 readjustment of the quark masses gives 5.374.
$m_{B_S^*} = 5.408$ to 5.410	

All this is rather impressive, whether one likes potential models of hadrons or not. So let us make now predictions:

$$m_{B_C} = 6.25 \text{ GeV}/c^2$$

$$m_{B_C^*} = 6.32 \text{ GeV}/c^2$$

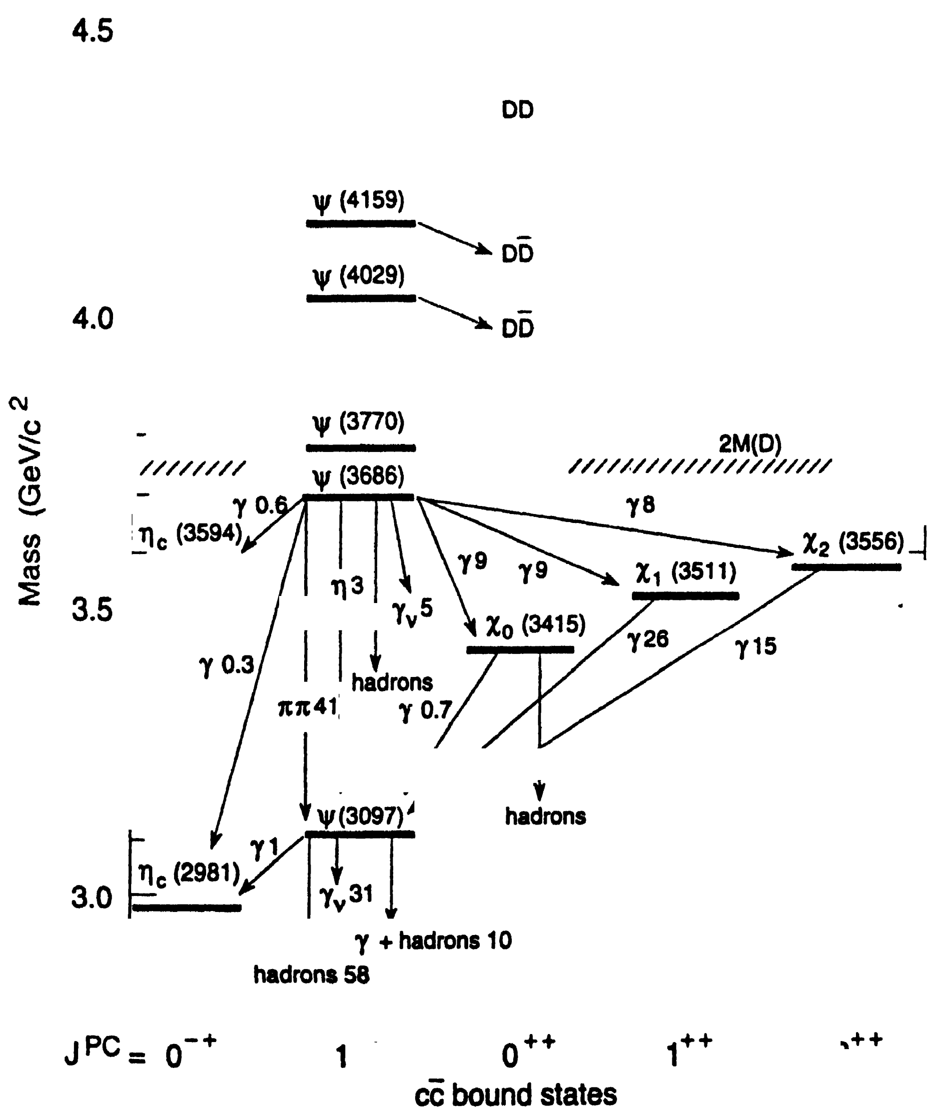

Figure 1

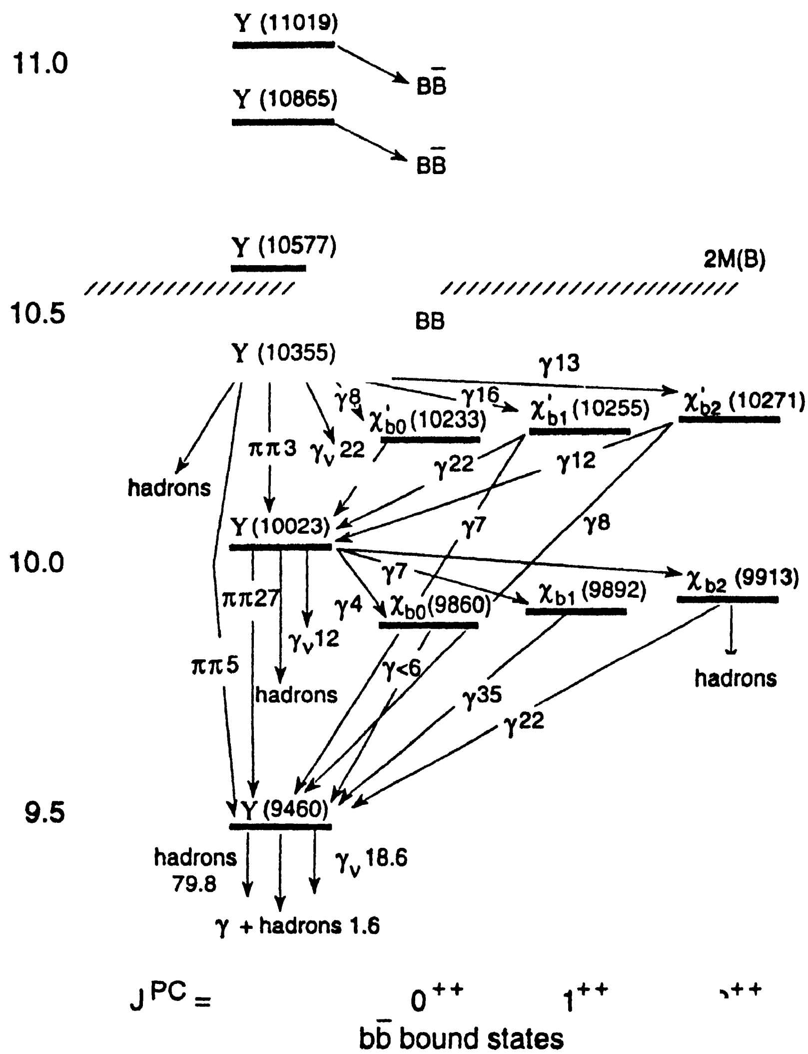

Figure 2

In any case we expect, from concavity properties of the Schrödinger equation

$$M_{B_C^*} > \frac{1}{2}(M_\Upsilon + M_{J/\psi}) = 6.28 \text{ GeV}/c^2 .$$

So, all we have to do is to wait and see!

More refined predictions can be made on the spacings of the $L = 1$ multiplet and in particular for the location of the singlet P state, assuming

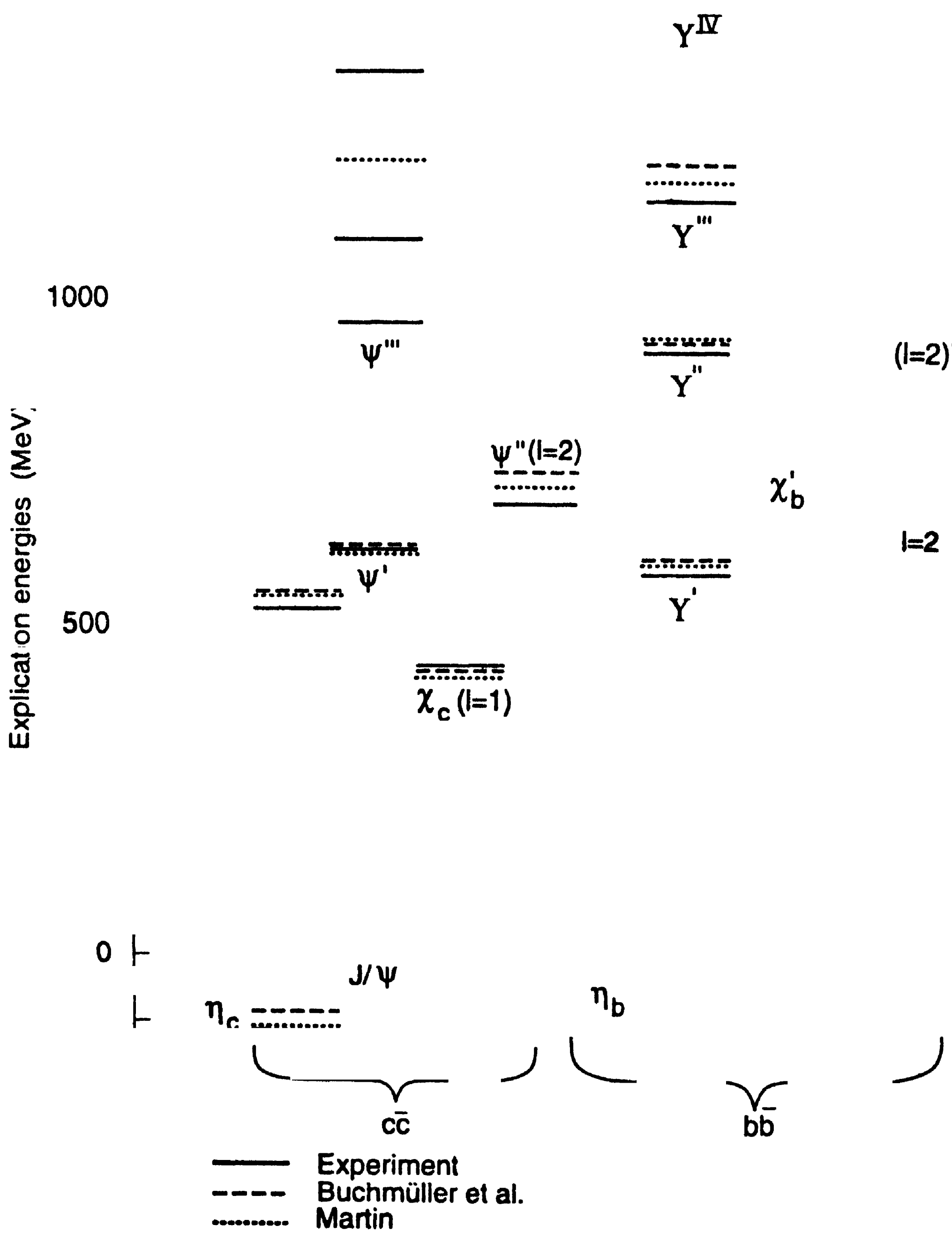
Explication energies (MeV)
1000
500
0
Υ^{IV}
Υ'''
Υ''
Υ'
ψ'''
$\psi''(l=2)$
ψ'
$\chi_c\,(l=1)$
χ'_b
(l=2)'
l=2
J/ψ
η_c
η_b
$c\bar{c}$
$b\bar{b}$
Experiment
Buchmüller et al.
Martin

Figure 3

that spin-dependent forces arise from a Breit Hamiltonian. Stubbe and I get[5]

$$3536 \pm 12 < M^{(c\bar{c})}_{{}^1P_1} < 3559 \pm 12 \text{ MeV}/c^2 .$$

This is to be compared with the experimental number obtained by a collaboration including Rosanna Cester-Regge from Torino, which is[6]

$$3526.1 \pm 0.1 \text{ GeV}/c^2 .$$

We also predict

$$9900.3 \pm 2.8 < M^{(b\bar{b})}_{{}^1P_1} < 9908.9 \pm 2.8 .$$

For baryons containing lighter quarks, the model is still less justified but gives also excellent results. In fact the most primitive approach, in which the central interaction between quarks is disregarded (or included in the quark masses) and only a hyperfine splitting QCD inspired is taken into account,

$$C \; \frac{\delta(\vec{r}_1 - \vec{r}_2)}{m_1 m_2} ,$$

gives already very impressive results as shown by Federman, Rubinstein and Talmi[7], Sakharov and Zeldovitch[8], and De Rujula, Georgi and Glashow[9]. They give, in particular, the first explanation of the $\Sigma - \Lambda$ mass difference if the ratio of the effective up mass to the strange mass is about 0.6.

The same philosophy works beautifully for magnetic moments[10] as illustrated in Table 1. In particular we notice that the recently measured magnetic moment of the Ω^- [11] is 3.29 ± 0.10 times the magnetic moment of the Λ. The agreement within 10 % with the naïve quark model should be considered as a success, not a failure!

Table 1

	EXP	μ/μ_P QUARK MODEL $m_u/m_s = 1$	QUARK MODEL $m_u/m_s = 0.652$
N	- 0.68	- 0.67	- 0.67
Λ	- 0.22 ± 0.02	- 0.333	- 0.207
Σ^+	0.85 ± 0.01	1	0.958
Σ^-	- 0.50 ± 0.09	- 0.333	- 0.37
Ξ^-	- 0.45 ± 0.05	- 0.666	- 0.50
Ω^-	- 0.74 ± 0.07	- 1	- 0.625

The agreement between calculated and measured baryon masses is still further improved if one takes into account a soft flavour independent potential, of the same type we considered for quarkonium, between quarks. This is illustrated, for instance by the calculation of Richard and Taxil, in Tables 2 and 3. Furthermore, almost model-independent predictions can be made on the masses of beautiful baryons[12] like

Table 2

	Theory	Experiment
N	input	.939
Δ	input	1.232
Λ^0	1.111	1.115
Σ	1.176	1.193
Ξ	1.304	1.318
Σ^*	1.392	1.383
Ξ^*	1.538	1.533
Ω^-	input	1.672
Λ_c	input	2.282
Σ_c	2.443	2.450
Σ_c^*	2.542	
$\Xi_c = A$	2.457	2.460
S	2.558	
S^*	2.663	
T^*	2.775	

Table 3

	De Rújula, Georgi, Glashow, Sakharov, Zeldovitch; Federmann, Rubinstein, Talmi	Richard, Taxil	Experiment
$\frac{M_{\Xi^*}-M_{\Xi}}{M_{\Sigma^*}-M_{\Sigma}}$	1	1.08	1.12
$\frac{2M_{\Sigma^*}+M_{\Sigma}-3M_{\Lambda}}{2(M_{\Delta}-M_N)}$	1	1.07	1.05
$\frac{3M_{\Lambda}+M_{\Sigma}}{2M_N+2M_{\Xi}}$ G.M.O. octet	1	1.005	1.005
$\frac{M_{\Sigma^*}-M_{\Delta}}{M_{\Xi^*}-M_{\Sigma^*}}$ G.M.O.	1	1.10	1.03
$\frac{M_{\Xi^*}-M_{\Sigma^*}}{M_{\Omega^-}-M_{\Xi^*}}$ decuplet	1	1.09	1.08

$$5379 < m_{\Lambda_b} < 5629 \text{ MeV}/c^2$$
$$5670 < m_{\Sigma_b} < 5826 \text{ MeV}/c^2$$

where the upper bounds come from convexity considerations and the lower bounds from the semi-empirical rule

$$V_{Q_1Q_2} = \frac{1}{2} V_{Q_1\bar{Q}_2}$$

The upper bound on Λ_b is very close to what experiment indicates. This rule also leads to a more refined prediction[13]

$$M_{\Omega^-} > 1659 \text{ GeV} ,$$

which fits with the explicit calculation of Richard[14]

$$M_{\Omega^-} = 1666 \text{ MeV} ,$$

only 6 MeV below the experimental number, which uses the parameters of my 1981 model and the above rule.

More recently, J.-M. Richard and I have again used the same model and the same rule to calculate the mass of the Ω_c (ssc, spin 1/2). We find [15] $M_{\Omega_c} = 2708$ MeV, while experiment [16] gives $M_{\Omega_c} = 2706.8 \text{ MeV} \pm 1$.

It is difficult not to be impressed by this incredible agreement. I believe that in spite of its imperfect basis the potential model of hadrons will remain the most predictive tool for many years, even if some other approaches, like lattice QCD, are more fundamental. To reach the same level of accuracy, the latter needs a computing power which is not yet available.

REFERENCES

1. R.H. Dalitz, Oxford International Conference on Elementary particles, Sept. 1965, ed. T.R. Walsh (Rutherford High Energy Laboratory, 1966), p. 157.
2. G. Zweig, CERN Preprint TH. 401 (1964), unpublished.
3. A. Martin, *Phys. Lett.* **100** (1981) 511.
4. W. Buchmüller, G. Grunberg and S.H.-H. Tye, *Phys. Rev. Lett.* **45** (1908) 103;
   W. Buchmüller and S.H.-H. Tye, *Phys. Rev.* **D24** (1981) 132.
5. J. Stubbe and A. Martin, *Phys. Lett.* **B271** (1991) 208.
6. E760 Collaboration, T.A. Armstrong et al., *Phys. Lett.* **69** (1992) 2337.
7. P. Federman, H.R. Rubinstein and I. Talmi, *Phys. Lett.* **22** (1966) 208.
8. A.D. Sakharov and Y.B. Zeldovich, *Acta Physica Hungarica* **22** (1967) 153;
   A.D. Sakharov, *Zh.Ehksp.Teor.Fiz.* **78** (1980) 2112.
9. A. De Rujula, H. Georgi and S.L. Glashow, *Phys. Rev.* **D12** (1980) 147.

10. S.B. Gerasimov, *Zh.Ehksp.Teor.Fiz.* **50** (1966)1599, English translation Soviet Phys.

11. N.B. Wallace et al., *Phys. Rev. Lett.* **74** (1995) 3732.

12. A. Martin, in "The Search for Charm, Beauty and Truth at High Energies", eds. G. Bellini and S.C.C. Ting (Plenum Press, New York and London, 1984), p. 501;
A. Martin and J.-M. Richard, *Phys. Lett.* **185B** (1987) 428.

13. J.-L. Basdevant, A. Martin and J.-M. Richard, *Nucl. Phys.* **B343** (1990) 69.

14. J.-M. Richard, *Phys. Lett.* **B100** (1981) 515.

15. A. Martin and J.-M. Richard, *Phys. Lett.* **B355** (1995) 345.

16. F. Dropmann (WA89 Collaboration), to appear in the proceedings of the XXX Rencontres de Moriond on Hadronic Interactions, March 1955, Ed. J. Tran Thanh Van, Editions Frontières, Gif-sur-Yvette.